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An Investigation of Thunderstorms as a Source of Short Period Mesospheric Gravity Waves

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For three months during the spring and early summer of 1988, low-light TV images showing wave structure in the near infrared hydroxyl (OH) nightglow emission (peak altitude ~87 km) were recorded from the Mountain Research Station near Nederland, Colorado (40.0°N, 105.6°W) as part of the AFOSR MAPSTAR'88 campaign. Well-defined, coherent wave patterns associated with the passage of short period (<1 hour) gravity waves were observed on a total of 22 occasions. One potential source of these waves has been studied using radar summary charts to identify regions of strong convection associated with the existence or development of thunderstorms. Comparison of the "storm" positions with the location and direction of motion of the OH patterns shows that there was always at least one disturbance suitably located in both space and time to have been the source. The analysis presented here is qualitative, but the large number of wave events associated with favorably located convective activity provides strong evidence for a relationship between the observed waves and storms. This result, although preliminary, suggests that thunderstorms are an important source of mesospheric gravity waves at this site and time of year.

1. INTRODUCTION

Internal atmospheric gravity waves, generated by sources in the troposphere, play an important role in governing the dynamical coupling between the lower and the upper atmos-pheric regions. In particular, small scale gravity waves with periods of <1 hour are now recognized to be a ubiquitous feature of the upper middle atmosphere [*Reid*, 1986]. These waves are responsible for as much as 70% of the wave induced transport that occurs in the mesosphere and lower thermosphere [*Fritts and Vincent*, 1987]. At such heights wave energy may be absorbed gradually into the mean flow or it may be deposited at a single "critical layer" if the background winds Doppler shift the wave frequency to zero [e.g., *Booker and Bretherton*, 1967]. Waves propagating through this region may also become unstable and break, depositing their energy in the form of small-scale turbulence. Variations in the seasonal and latitudinal abundance of short period gravity waves therefore can have a marked effect on the dynamics of the upper atmospheric circulation.

Observations of the hydroxyl (OH) nightglow emission, which originates at a mean altitude of ~87 km and has a night-time halfwidth of 5-8 km [*Baker and Stair*, 1988], provide an excellent method for remote sensing mesospheric gravity waves [e.g., *Armstrong*, 1982; *Takahashi et al.*, 1985; *Taylor et al.*, 1987]. Imaging studies are important as they provide unique information on the two-dimensional horizontal gravity wave parameters $(\lambda_x, v_x, \tau_{obs})$, over a large geographic area (up to $\sim 10^6$ km^2) and with a high spatial and temporal resolution [*Taylor et al.*, 1993]. In particular, image data are valuable for investigating gravity wave sources as they contain unambiguous information on the frequency of occurrence, geographic location, orientation, and the horizontal direction of propagation of the waves [*Taylor and Hapgood*, 1988; *Taylor and Edwards*, 1991].

Any disturbance that introduces a change in the atmosphere on a time scale of a few minutes to several hours may be capable of generating gravity waves. Tropospheric sources are thought to be important at all latitudes as waves created near the earth's surface may grow considerably in amplitude as they propagate energy upwards. Weather related disturb-ances such as jet streams, fronts, depressions, severe storms and winds blowing over prominent topographic features therefore may be responsible for many of the wave-like motions that frequently permeate the upper neutral atmosphere and the ionosphere. Several attempts have been made in the past to associate tropospheric sources with various upper atmospheric wave phenomena [e.g., *Hines*, 1968; *Röttger*, 1977; *Freund and Jacka*, 1979; *Hung et al.*, 1979]. To date, most of these studies have proven inconclusive and only on rare occasions has an individual source been positively identified. This is because there are often several potential sources present and because the effects of wind filtering on the gravity waves as they propagate upwards are usually unknown. As a consequence, the spatial distribution and the temporal variability of the wave sources primarily responsible for the transport of momentum into the upper atmosphere remain obscure.

One potential source mechanism that is thought to be quite efficient at generating short period gravity waves is strong tropospheric convection that often culminates as thunder-storms [*Pierce and Coroniti*, 1966]. In a previous study we successfully identified an isolated thunderstorm as a source of short period (~15 min) gravity waves imaged in the OH, Na (589.2 nm) and OI (557.7 nm) nightglow emissions [*Taylor and Hapgood*, 1988]. In this report we build on this result by using a series of all-sky OH data recorded over a three month period to determine the relationship between the occurrence of regions of strong convection and the appearance of short period mesospheric gravity waves.

2. INSTRUMENTATION

Measurements of the near infrared (NIR) OH nightglow emission were made using a low light, Image Isocon TV system capable of obtaining good quality images of wave structure with an integration time of typically 2–5 s [*Taylor et al.*, 1993]. The TV camera was fitted with a Nikon 8 mm f/2.8 "fish eye" lens, giving an all-sky (180°) field of view, and a

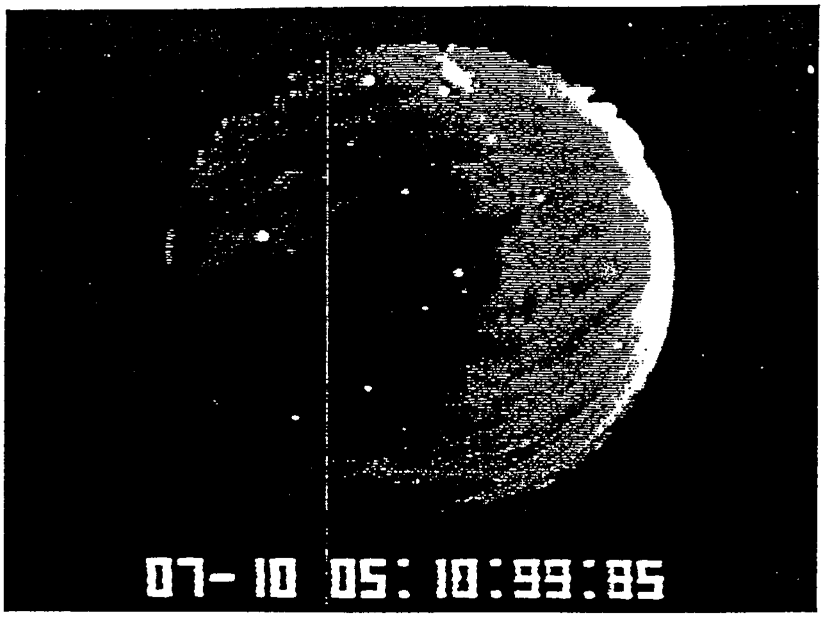

Fig. 1. All-sky image showing coherent NIR OH wave structure extending over the entire field of view. The data were obtained on 10 July at 05:10 UT using an integration time of 1.5 s [*Taylor et al., 1993*]. The bright band intersecting the wave display at an acute angle is the Milky Way. The apparent increase in sky brightness to the east is due to scattered light from cities on the Colorado plains.

Schott RG715 glass filter limiting the bandwidth of the observations to 715-810 nm. This region of the nightglow spectrum is dominated by several OH Meinel band emissions which have an integrated intensity of ~2 kR. Wave structure was detectable at all azimuths up to a maximum range of ~600 km (limited by the local horizon) which corresponds to a nominal search area ~10^6 km^2 (for an emission altitude of 87 km).

3. MEASUREMENTS

To investigate any association between the occurrence of "storms" and the subsequent appearanceof short period, mesospheric gravity waves, data from a three month cam-paign conducted during spring and early summer of 1988 (new moon periods May 11-22, June 7-22, and July 9-18) were analyzed. The measurements were made from the Mountain Research Station (MRS) near Nederland, Colorado (40.0°N, 105.6°W, 3050m) which is located near the eastern edge of the Rocky Mountains. This region is well known for its strong convective activity and thunderstorms were observed to occur with increasing frequency during this time. Well defined OH wave patterns were detected on a total of 22 occasions, 18 of which have yielded accurate measurements (see Table 1). Figure 1 is an example of a coherent OH wave display extending over the entire camera field [*Taylor et al.*, 1993]. The image was obtained on July 10 at 05:10 UT during an unusually high contrast event and shows numerous near east-west aligned wave fronts. Data were obtained for ~4 hours during which time the wave forms were observed to move uniformly towards the north. Several convective regions were detected on this occasions but only one occurred at an appropriate azimuth to have been an acceptable candidate source (see Results). Most of the wave patterns were less conspicuous than this display but all of them appeared as a set of well-formed elongated structures, usually extending over a limited area of the camera's field.

4. ANALYSIS PROCEDURE

The data have been analyzed to determine the geographic location and orientation of the wave patterns, their time of occurrence and where possible their horizontal wavelengths (λ_x), phasespeeds (v_x), and observed periods (τ_{obs}). The images were calibrated first in terms of elevation and azimuth using the right ascension and declination of several known stars within the all-sky field [*Hapgood and Taylor*, 1982]. Ground maps showing the position and motion of the wave forms as a function of time were then calculated for each display (assuming an emission altitude of 87 km), from which its average horizontal wavelength and velocity was determined. Only those displays that exhibited well-defined structures subtending elevations >5° have been used in this study.

Radar summary charts covering the continental USA (one per hour) were used to identify regions of strong convection associated with thunderstorm activity. In May the number of convection zones on any one day were few, but in June and July the summary charts were considerably more complex. Measurements of the geographic location, altitude and time of occurrence of only those disturbances that achieved ~10 km in height (i.e. storms approaching the tropopause region) were made. However, on some occas-ions, mainly during May, lower altitude isolated disturbances were also considered (see Discussion).

Linear gravity wave theory indicates that the range from the tropospheric source to the region of observation of the wave in the upper atmosphere is strongly dependent on its periodicity [*Hines*, 1967]. For an isothermal, stationary atmosphere, the minimum horizontal range (R_{min}) from the source to the point of intersection with an airglow layer is given by:

$$R_{min} = (h_a - h_s)\sqrt{\frac{\tau^2}{\tau_b^2} - 1} \qquad (1)$$

where h_a and h_s are the heights of the airglow layer and the gravity wave source, τ_b is the Brunt-Väisälä period, and τ is the intrinsic period of the wave (which equals its observed period in a stationary atmosphere) [*Taylor and Hapgood*, 1988]. This relationship holds provided the vertical extent of the wave source is not large (i.e. typically <8 km). For a convective source such as a thunderstorm h_s would be about 5-15 km. Using a height-averaged value of $\tau_b = 5.5 \pm 0.5$ min and a wave period of 1 hour (which includes all the observations listed in Table 1, with the exception of June 20a display), an upper limit for R_{min} would be ~1,000 km. Many of the observed wave motions exhibited $\tau_{obs} <<$ 1 hour indicating ground ranges of only a few hundred kilometers. However, as wave propagation can be affected significantly by background winds in the stratosphere and mesosphere (which are unknown), the actual horizontal range may vary considerably. Thus, to encompass as many candidate sources as practical, a search region 1,000 km in radius (extending from the Mexican to the Canadian border), was used for all wave events.

The time taken for wave energy emanating from a tropo-spheric source to reach the upper mesosphere is dependent upon the wave's group velocity. Assuming an isothermal, stationary atmosphere *Taylor and Hapgood* [1988] calculated a time of flight of 6 ± 0.5 hrs for a wave of period 17 min, originating from a storm at a range of ~500 km, and propa-gating with a horizontal group velocity of 23 ± 2 ms^{-1} to reach the OH layer. Waves generated near the limit of our search region, or waves exhibiting significantly lower group velocities would be expected to take several hours longer. As background winds also affect the group velocity of the waves as well as their path length through the intervening atmosphere, radar summary charts were investigated for intervals up to 14 hours prior to each display in an attempt to ensure sufficient time for wave propagation (equivalent to a horizontal group speed of 20 ms^{-1} for a source located at the limit of the search area).

5. RESULTS

5.1. *Wave Measurements*

Table 1 summarizes the results of the image analysis. A total of 18 events were recorded where λ_x and the wave azimuth (i.e. the horizontal direction of motion) were measured. However, only 14 of these displays gave accurate measurements of v_x and hence τ_{obs}. The horizontal wave-lengths ranged from 19-70 km yielding a mean value of 36 km for the campaign. The spread in the individual measure-ments suggests no major difference from month to month, but the average value was found to decrease systematically from 44 km in May to 29 km in July. The horizontal phase speeds ranged from 14 to 42 ms^{-1} and within the limits of the measurements showed no month to month variation (average value = 28 ms^{-1}). The observed periods of the wave patterns (with the exception of June 20a event), were all less than 1 hour. The average period for May (29 min) and June (32 min; excluding June 20a) were similar, but somewhat higher than the mean for July (19 min), reflecting the lower average λ_x for this month. These parameters are typical of many of the short period wave events reported in the literature [e.g., *Reid,* 1986].

TABLE 1. Summary of Image Measurements

UT Date 1988	Data Interval (UT)	λ_x (km)	v_x (m/s)	τ_{obs} (min)	Wave Azi (±5°)
May 13	7:50-8:30	38±3	30±2	21.0	90
May 14	6:00	56±5	-	-	120
May 16	8:30-10:00	70±2	21±2	55.5	20
May 17	7:00-9:00	26±2	28±2	15.5	40
May 21	9:35-10:05	30±6	22±4	23.0	125
Mean	-	44	25.3	28.8	-
Jun 12	6:54	41±2	-	-	10
Jun 17	7:40-8:50	41±14	22±1	31	15
Jun 19	8:30	19±5	-	-	55
Jun 20a	8:00-9:00	35±5	5±2	117.0	15
Jun 20b	8:00-9:00	21±2	42±2	8.0	340
Jun 21a	6:10-8:45	50±5	18±3	46	80
Jun 21b	6:10-8:45	35±9	14±3	42	20
Mean	-	34.5	29.6	48.8 (32)*	-
Jul 10	5:10-6:40	21±5	20±1	23.0	15
Jul 12	4:50-5:50	30±5	23±3	22.0	30
Jul 15	6:42	30±3	-	-	345
Jul 16	5:20-8:40	45±2	28±2	27	140
Jul 17	5:30-7:30	21±4	32±4	11	345
Jul 18	5:30-6:40	25±5	37±3	11	0
Mean	-	28.7	28	18.8	-

* Without June 20a data

Table 1 shows that a distinct preference for wave propa-gation towards the north existed during this campaign (with 68% of the wave azimuths within ±40°N). In particular, it was found that none of the OH displays exhibited a signifi-cant westward component of motion suggesting that the gravity waves were subject to considerable directional filtering. *Taylor et al.* [1993] have shown that this anisotropy in wave propagation can be attributed solely to the effects of "critical layer" filtering of the gravity waves by background winds in the stratosphere and lower mesosphere. This result is used in the next section to help discriminate between potential convective sources.

5.2. *Thunderstorm Comparison*

The OH patterns were compared with the ensemble of "storm" maps to determine any obvious candidate sources. (Note, the term storm refers to any region of strong convection as determined from the radar summary charts.) Figure 2 shows four example maps comparing OH wave data with radar summary data; for

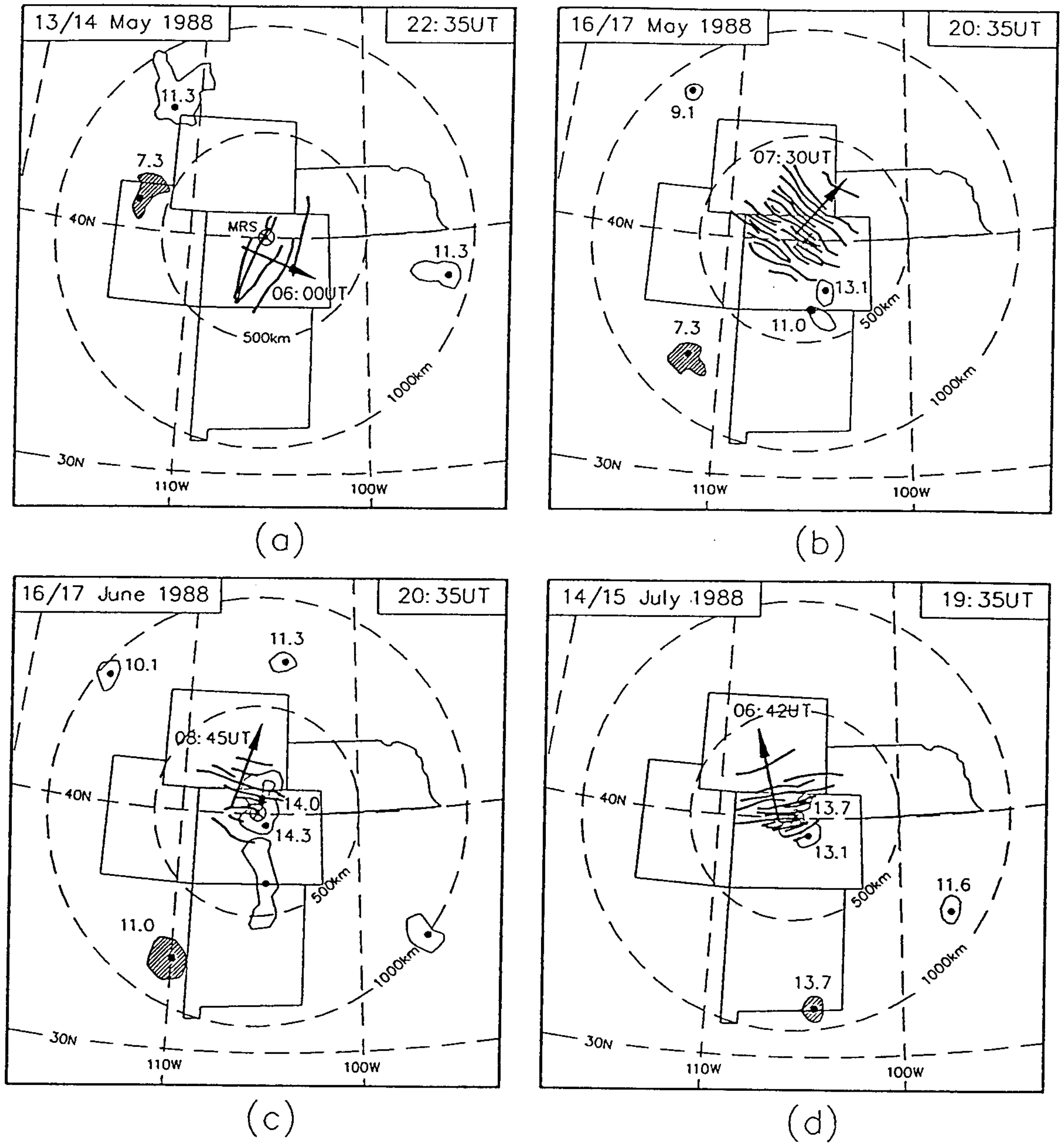

Fig. 2. Four example maps comparing the OH wave structure (bold lines) with radar summary data. The "storm" positions are indicated by the irregular areas marked with a black spot, the numbers give maximum cloud height in km. The dashed outer circle indicates the 1,000 km radius search area. In each example the "candidate storm" is marked by the hatched area. The arrows show the direction of motion of the waves.

two displays in May, and one each in June and July. Figure 2a shows the wave display of 14 May recorded at 06:00 UT superimposed on the storm map for 13 May at 22:35 UT (time interval 7.5 hours). On this occasion, meteorological cloud limited the measurements of the wave parameters to λ_x only. However, a sufficient number of images were recorded to determine the wave's direction of motion. Three storm centers existed within the search area at this time, two to the west/northwest of MRS and one to the east. The storm to the west at a range of about 650 km (shaded area) appears to be located well in both position and time to be a candidate source. The disturbance to the east was potentially more powerful (cloud tops reaching 11.3 km), but its position was not consistent with the observed direction of wave motion (indicated by the arrow). This fact, together with the result that the prevailing background winds tend to limit westward wave propagation, indicates that this storm was not the source of the waves. In total, five regions of strong convection occurred within the search area/interval on this occasion, but only one (the storm to the west) was suitably located to have been the source of the gravity waves.

Figure 2b shows a more extensive wave pattern recorded on 17 May at 07:30 UT (τ_{obs} = 15.5 min). The direction of motion of the waves (towards the northeast) is quite different from the previous display. In this example, the radar summary map is plotted for 20:35 UT (time interval 11 hours) and shows two storm regions to the south, one to the northwest, and one to the southwest. This latter disturbance (shaded area) occurred at a range of ~800 km and was favorably oriented to be a candidate source. A second candidate source was also found on this occasion at a larger range (~1,000 km), but at a shorter average time interval (~7 hours). Figures 2c and 2d show similar situat-ions for two more displays observed on 17 June and 15 July. On each of these nights several storms occurred within the source area/interval. Both wave displays exhibited north-ward progression and in each case more than one candidate source was identified.

A summary of the results of this study, for each month, is given in Tables 2, 3 and 4, which include information on the candidate storms: their altitudes, range from MRS and the average time intervals. This latter parameter is a measure of the mean time between the storm occurrence and the time of the wave observations listed in Table 1. As meteorological cloud often limited the available observing time this number is only an approximation for the actual time of separation. The deviation in azimuth of each of these candidate sources from the direction of wave propagation is also listed. Because of uncertainties in positioning individual storms (due to their evolution and motion), all storms within ± 20° of the nominal wave azimuth were considered as candidate sources. However, the majority of these disturbances (77%), occurred within ± 10°. As expected the number of candidate sources and their heights were observed to increase considerably from May to July.

6. DISCUSSION

On every occasion when OH wave measurements were possible (a total of 18 displays) there was always at least one storm favorably located in both space and time to have been the source. This is a remarkable result considering the observed distribution of the potential sources. During the course of the campaign it would not have been surprising to find one or two favorably located candidate sources by chance, given the selection criteria used. However, the large number of wave events that can be associated with regions of strong convection suggests that this correlation was most probably not due to chance alone. On a case study basis the data recorded in May provided the most critical test of this result as far fewer thunderstorms occurred during this month yet acceptable candidate storms were found on each of the five nights when wave structure was observed (see Table 2). Candidate storms were found within the nominal 1,000 km radius search area for all but one of the 18 events. For the display of 13 May (τ_{obs} = 21 min) a disturbance located at a range of 1,400 km was identified. On this occasion the background winds may have substantially increased the path length of the gravity waves through the intervening atmosphere. For this reason several other potential candidate sources outside the nominal search area have been included in the summary Tables where appropriate. The mean time interval from storm occurrence to wave observation varied from about 3-12 hours and the ground distance separating the storm centers from MRS (over which the wave structures were measured) ranged from 200-1,400 km. In June and July more than one candidate storm was often identified. Although estimates of the ground range, time of flight, and deviation from the nominal wave azimuth may be used to help choose between these sources, considerable uncertainty would remain due to the unknown influence of the back-ground winds. A better method of distinguishing between several potential sources would be to trace the path of the waves through the atmosphere for each event. Dr T.F. Tuan (University of Cincinnati) is currently developing a ray tracing model for a realistic atmosphere, based on climat-ological background winds and numerical tidal modes, to investigate further the candidate storms identified here. The results of this modelling study will help significantly to quantify this apparent correlation.

Several researchers have published convincing evidence in support of the generation of short period gravity waves by thunderstorms [e.g., *Curry and Murty* 1974; *Balachandran* 1980; *Larsen et al.*, 1982]. However, evidence establishing the propagation of these storm-induced waves into the upper neutral atmosphere and the ionosphere is far less common [*Röttger*, 1977; *Taylor and Hapgood*, 1988]. This study indicates that thunderstorms, or convective regions associated with their development, are a potentially important source of short period wave energy reaching the upper atmosphere at this time of the year. Because cumulus convection associated with the development of thunder cells (typical radius ~10 km at mid-latitudes) produces strong vertical updrafts, thunderstorms are particularly well suited to the generation of short horizontal wavelength (a few tens of km) gravity waves. *Pierce and Coroniti [1966]* proposed penetrative convection of the thunder cell at the tropopause as one mechanism for generating waves with periods a few tens of minutes (dependent upon the temperature gradient at the tropopause), similar to those observed in the OH emission. The candidate storms identified in this study were not always the highest, most prominent disturbances present on any one occasion (see Tables) and their altitudes varied considerably over the three month period (ranging from 6 to 18 km). This suggests that many vertically developing, convective systems may be capable of generating gravity waves of period <1 hour and not just those storm cells reaching tropopause heights.

TABLE 2. Results of Thunderstorm Comparison Study for May

UT Date 1988	Maximum Height (km)	Range to MRS (km)	Time Interval (hrs)	Deviation From Wave Azi (±5°)
May 13	6.1	1400	8 ± 3	15
May 14	7.3	650	9 ± 1	0
May 16	12.2	450	10 ± 2	10
May 17	7.3	800	12 ± 2	5
	-	1000	7 ± 2	0
May 21	8.5	550	8 ± 2	20

TABLE 3. Results of Thunderstorm Comparison Study for June

UT Date 1988	Maximum Altitude (km)	Range to MRS (km)	Time Interval (hrs)	Deviation from Wave Azi (±5°)
Jun 12	-	600	6 ± 3	10
	14.0	900	3 ± 2	15
Jun 17	11.0	750	10 ± 3	10
	12.1	200	7 ± 2	20
	-	600	5 ± 1	5
Jun 19	-	750	12 ± 1	5
	9.8	1150	11 ± 1	10
	-	600	5 ± 1	5
Jun 20a	12.2	300	12 ± 7	0
	11.6	900	5 ± 1	20
Jun 20b	12.2	300	9 ± 4	5
Jun 21a	13.1	800	11 ± 3	20
	11.9	750	12 ± 3	5
	12.8	1300	8 ± 3	10
Jun 21b	11.0	300	11 ± 3	25

TABLE 4. Results of Thunderstorm Comparison Study for July

UT Date 1988	Maximum Height (km)	Range to MRS (km)	Time Interval (hrs)	Deviation From Wave Azi (±5°)
Jul 10	-	800	10 ± 2	0
Jul 12	11.3	800	8 ± 3	5
	-	400	7 ± 3	0
Jul 15	15.2	1150	9 ± 2	5
	13.7	950	9 ± 2	5
	14.6	950	4 ± 2	0
Jul 16	17.1	700	7 ± 3	10
	11.3	800	7 ± 3	20
Jul 17	12.8	1000	11 ± 2	10
	17.7	750	8 ± 5	0
	12.2	300	9 ± 3	5
Jul 18	15.5	1200	7 ± 4	10
	16.2	800	7 ± 3	15
	13.1	300	7 ± 3	0

The anisotropy in the observed distribution of wave azimuths agrees well with the hypothesis that waves were launched by storm systems that were subject to considerable "critical layer" directional filtering [*Taylor et al.*, 1993]. This result may be used to account for the apparent absence of wave structure associated with potentially powerful convective sources that often developed to the east of the optical site. However, on several occasions storms were also observed at azimuths which generally should not have been restricted by the background winds, and yet little evidence of wave structure associated with these potential sources was found. Indeed, on only two occasions (June 20 and 21) were more than one OH wave pattern discerned. This is a surprising observation and may be connected with the sensitivity of the TV system. Recent all-sky OH observations using a new generation of solid state (CCD) imagers indicate that it is not uncommon to detect several different wave patterns during the course of a night. However, the brightness and contrast of these displays can vary considerably. Thus it seems plausible that the Isocon camera used for this study recorded only the most prominent wave motions on any one occasion, and that gravity waves generated by other storms may have gone undetected.

The result of this qualitative study suggest a direct link between storm related convection and the appearance of short period OH wave structure, but should be viewed as preliminary. Other tropospheric sources, thought to be capable of generating gravity waves (e.g. fronts, depressions, jet streams and wind flow over topography), also existed during this campaign. The all-sky observations were made from a mountainous site, but orographically generated waves (stationary waves) can be discounted on most occasions as significant phase progression, of typically a few tens of ms^{-1} was observed in each case (with the exception of the June 20a display which moved at a speed of 5 ± 2 ms^{-1}). In-situ sources such as the breakdown of long period tidal-type waves may also have been present [*Taylor and Edwards*, 1991]. The near linear appearance of several wave displays suggests gravity wave generation by an extended source region (e.g a front) rather than a discrete "point-like" convective region, but this argument is conditional on the range of the source from MRS, which we have shown may be quite large, depending upon the wave period and the pre-vailing atmospheric conditions. A detailed investigation of the occurrence of these potential sources and their assoc-iation (if any) with the OH wave events is in progress.

7. SUMMARY

Short period (<1 hour) gravity waves of varying scale sizes and phase speeds were imaged on nearly every night that the sky was clear during the three month campaign. The wave forms often appeared as coherent, quasi-linear patterns with lifetimes of a few hours. A striking result of this investi-gation is that at least one candidate storm was found for every occasion that OH wave structure was detected. The observed distribution and abundance of the storms does not indicate that this result was due to chance alone. These observations, although preliminary, support the hypothesis that thunderstorms may be an important and abundant source of short period gravity waves capable of reaching meso-spheric heights. The characterization of such wave events ($\lambda_x, v_x, \tau_{obs}$) and the investigation of seasonal variations in source anisotropy is of considerable importance for modelling studies of the global-scale circulation.

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